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# **Use of metakaolin with stabilised extruded earth masonry units**

Dr Daniel Maskell<sup>1</sup>, Dr Andrew Heath<sup>1</sup> and Prof Pete Walker<sup>1</sup>

<sup>1</sup>BRE Centre for innovative Construction Materials,  
Department of Architecture and Civil Engineering,  
University of Bath,  
Bath,  
United Kingdom

Corresponding Author: Dr Daniel Maskell, D.Maskell@bath.ac.uk

## **Keywords**

**Cement, Lime, Compressed Earth Block, Natural Building Material, Strength**

## **Abstract**

Modern earth masonry increasingly utilises conventional methods of extruded fired brick production for the manufacture of unfired earth bricks. However, these bricks are not generally recommended for structural applications due to their loss of strength under elevated moisture contents. Disproportionate collapse could occur following accidental or intentional wetting of a 100mm thick load bearing unfired earth wall. Unfired clay bricks can be chemically stabilised, typically by the addition of cement or lime to improve wet strength. However, the use of such binders has been shown to be ineffective for silt and clay rich soils used for extruded bricks.

The research presented in this paper demonstrates the change in compressive strength that can be achieved through the addition of metakaolin to cement and lime stabilised extruded earth masonry. Small-scale bricks were manufactured and tested in compression in both ambient environmental conditions and following a minimum of 16 hours of full submersion in water.

Though the addition of metakaolin did not universally improve performance. This research presents a feasible solution using 5% lime and 10% metakaolin, that would allow unfired extruded earth masonry units to be used for structural applications.

## 1 Introduction

There are growing concerns over the embodied environmental impact of construction materials (Sturgis and Roberts, 2010). Whilst earthen forms of construction have been used for thousands of years, there is a renewed interest due to its low embodied impact (Morton, 2006). For this benefit to have a national impact modern methods of production and construction with earth are required. Modern earth masonry that uses commercial methods of brick manufacture can be utilised for unfired earth brick production (Morton, 2006, Heath et al., 2009 and Maskell et al., 2014)

Commercial extruded earth brick production uses the same methods of manufacture as fired brick units without the firing. This produces conventional sized bricks and results in a wall thickness of approximately 100mm for internal partitions and inner leafs. Heath et al. (2012) demonstrated the structural feasibility of unfired clay bricks for use in two to three storey domestic buildings, where lightweight concrete blocks, with a compressive strength of 2.9MPa, would typically be specified. However, at elevated moisture contents the compressive strength of the units reduces which can lead to complete loss of structural integrity (Heath et al., 2009). When unfired earth constructions are subjected to these conditions, even as an accidental case, then clearly disproportionate collapse could occur. This has led to a defined minimum strength criteria for the unfired brick units as 2.9 MPa under 'dry' conditions and 1.0 MPa under 'wet' conditions, where 'dry' conditions are under ambient temperatures and relative humidity and 'wet' conditions are following over 16 hours being fully submerged in water (Maskell et al., 2014).

Maskell et al. (2014) performed a preliminary investigation into cement and lime stabilised extruded soil bricks. Stabiliser types and contents commonly used for compressed earth blocks were not always appropriate for extruded bricks, which typically had a higher clay and silt content than in compressed earth blocks. Cement and lime both increased the 'dry' and 'wet' compressive strength, with the performance depending on the mass fraction and initial curing temperature. While cement achieved greater 'dry' compressive strengths, the addition of lime achieved greater

'wet' compressive strengths. The addition of 5% lime, with an Initially Curing Temperature (ICT) of 105°C achieved a 'wet' compressive strength of 1.02 MPa. Considering the variability of these results, the lower bound 95% confidence interval of this average strength is 0.85 MPa, therefore not meeting the minimum 'wet' strength criteria.

The performance of a stabiliser and the fundamental binding mechanism, may be improved by the addition of a secondary stabiliser or pozzolan. There has been growing interest in the use of industrial waste and by-products such as Ground Granulated Blast-furnace Slag (GGBS) and fly ash. Heath et al. (2013) questions the future availability of slags and fly ash, as almost all of the slag is accounted for in Portland cement blends and fly ash production will dwindle in the UK due to a reduction in reliance on coal for power generation. Metakaolin is an alternative to GGBS and Pulverised Fly Ash (PFA) used within concrete manufacture based on Ordinary Portland Cement and geopolymers. Within the UK there are proven reserves of kaolin which could be used to produce approximately 1.4 million tonnes of metakaolin per annum (Heath et al., 2013). Although the metakaolin is relatively highly processed material, its use and cost could be justified within large scale commercial manufacture where there are benefits of economies of scale.

The focus of this paper is the use of metakaolin as a secondary stabiliser for modern earth masonry units. The addition of various mass fractions of metakaolin to cement and lime stabilised extruded earth masonry units are described. Small-scale extruded bricks were manufactured using brick soil typically used for the commercial production of fired bricks, which has been shown to be a suitable representation of full-scale bricks. For the purposes of this paper, a successful stabilisation method is one that achieves a saturated or 'wet' compressive strength of 1MPa, without the reduction of a 'dry' compressive strength tested in ambient conditions.

## **2 Background**

### **2.1 Metakaolin**

Metakaolin is a dehydroxylated form of kaolinite, following the chemical removal of the bonded hydroxyl ions from the kaolinite minerals, typically through heating to approximately 750°C. As kaolin contains no carbonates, no CO<sub>2</sub> is released during heating leading to reduced embodied

CO<sub>2</sub> in the final materials when replacing cement or lime. Due to the pozzolanic properties of metakaolin, there has been growing interest in its use as a cement replacement as well as an addition to lime or for geopolymer concrete (Wang et al., 2005; De Gutiérrez et al., 2008; Ramezani pour and Jovein, 2012). Metakaolin has the chemical structure of Al<sub>2</sub>Si<sub>2</sub>O<sub>7</sub> and exhibits pozzolanic properties that can be potentially utilised to achieve the required strength criteria of extruded unfired earth bricks.

## 2.2 Stabilisation mechanisms

Metakaolin provides a source of alumina and silica for additional hydration reactions to occur in with both cement and lime. The reactions involving metakaolin for concrete applications has been reviewed by Sabir et al. (2001). The typical pozzolanic activation of metakaolin is with Calcium Hydroxide (CH) that is both the chemical make-up of hydrated lime and also a hydration product from Ordinary Portland Cement (OPC). In addition to this reaction Wild et al. (1996) identifies that the metakaolin will accelerate the OPC hydration reactions as described later and act as a filler.. It is expected that these reactions will be key for strength development for unfired earth masonry as demonstrated with more conventional concrete applications.

During the hydration of cement, 16%-20% of CH, commonly referred to as Portlandite, is produced from the OPC (Pearson et al., 1983). Pozzolanic materials, such as metakaolin, can react with the CH to produce addition cementitious gels. Murat (1983) presents three competitive hydration reactions between metakaolin and CH that produce Calcium Silicate Hydrate (C-S-H) gels as well as Calcium Aluminate Hydrate (C-A-H) and aluminosilicate hydrates that yield similar properties to Portland Cement (Ambroise et al., 1994). Reactions between metakaolin and tricalcium silicate (C<sub>3</sub>S) and tricalcium aluminate (C<sub>3</sub>A), also present within cement, were investigated by Ambroise et al., (1994). While no effect on C<sub>3</sub>A was identified, the presence of metakaolin was shown to accelerate the hydration C<sub>3</sub>S up to a ratio of C<sub>3</sub>S:metakaolin of 1.40 with additional metakaolin acting as a filler. The same study also shows that calcium, alumina silica hydrates can precipitate within pore spaces that help to increase durability.

Sabir et al. (2001) comment that there is minimal strength gain for more than 15% metakaolin replacement of binder mass. The acceleration of pozzolanic reactions is typically utilised for early strength development of concrete (Sabir et al., 2001). Variations in initial curing temperature, similar to used by Maskell et al. (2014) for stabilised extruded earth masonry units development, have been shown to have a significant influence; with the increase in curing temperature to 50°C permitting a reduction of 50% of the amount of metakaolin required to achieve optimum performance (Sabir et al., 2001).

The reaction of metakaolin and lime in water has been discussed by Cabrera and Rojas (2001) and Konan et al. (2009). Konan et al. (2009) note that the reaction between metakaolin and lime forms CSH gel and aluminate phases, in accordance with the reaction with Portlandite as expected. In addition to the pozzolanic reactions that occur, the lime will also carbonate with Cabrera and Rojas (2001) and Fortes-Revilla et al. (2006) both commenting that the reaction kinetic varies depending on differing temperature and relative humidity and will result in differing properties depending on which reaction is dominant.

How these reactions between cement or lime and metakaolin are influenced by potentially reactive aluminosilicate natural clay minerals is not described in the scientific literature. However, the increase in the production of cementitious gels that can at least encapsulate the clay particles, treating them as effectively very fine aggregate in a cementitious matrix is expected to improve the mechanical properties and in particular the water resistance of the masonry unit. Maskell et al., (2014) commented that a reaction between lime and the clay minerals resulted in the improved 'wet' strength compared to the cement. While the addition of metakaolin will increase the quantity of cementitious materials, if the lime and metakaolin react preferentially without the incorporation of the clay minerals, then this may result in reduced strength and water resistance, both of which are undesirable.

Due to the potential of metakaolin to improve the mechanical and durability properties of extruded unfired stabilised bricks, its use as a secondary stabiliser is investigated in this paper. While much of the previous work has focused on replacement of OPC, this study will consider it as a

secondary stabiliser. The interaction of the soil both physically and chemically with the primary stabilisation additive affects its performance, as discussed by Maskell et al. (2014) and the presence of uncalcined kaolin and other clay minerals may affect performance. The literature regarding the use of metakaolin for strength and durability have focused on the manufacture of either non-specific binders or concretes (Sabir et al., 2001). Although there is information in the scientific literature concerning the reactions between metakaolin and primary stabilisers, there is no available literature concerning how these binders interact with soil for any earthen construction method. The hydration reactions with additional metakaolin will require additional water, however extruded bricks are extruded at the plastic limit, which will be less moisture than the required for complete hydration. While this may limit the scope for use of pozzolans for soil stabilization, it is also required for the manufacture of the bricks. Khatib, (2008) investigated low water to binder ratios for metakaolin concretes with no decrease in strength compared than higher ratios (Wild and Khatib, 1997).

The aim of this research is to investigate a suitable combination of primary stabiliser and metakaolin for use with unfired extruded earth bricks. A suitable combination is one that meets the minimum wet and dry compressive strengths indicating the bricks potential to be used structurally.

### **3 Materials and Methods**

#### **3.1 Brick Soil**

There is a range of physical and chemical properties of soils used for commercial extruded fired brick production (Maskell et al, 2013). Heath et al. (2009) demonstrated the suitability of these materials to be used for unfired brick production. The soils for brick manufacture are classified as predominantly silt sized with the behaviour of a low plasticity clay. The soil used for this investigation has the same properties of the soil used and described by Maskell et al. (2014) and is a dark brown sandy silt with the properties given in Table 1. The dominant potentially reactive phyllosilicate minerals are Kaolinite (31%) and Illite (13% of total mass), although Smectite and Chlorite is also present.

Properties	%
<b>Physical Properties</b>	
Liquid Limit	24
Plasticity Index	8
Linear Shrinkage	6
<b>Particle Grading</b>	
Sand	33
Silt	46
Clay	16
<b>Mineral Content</b>	
Siderite	2
Hematite	3
Smectite	3
Chlorite	6
Illite	16
Kaolinite	31
Quartz	39
<b>Oxide Composition (wt.)</b>	
SiO <sub>2</sub>	57.48
Al <sub>2</sub> O <sub>3</sub>	17.04
Fe <sub>2</sub> O <sub>3</sub>	11.36
K <sub>2</sub> O	3.72
TiO <sub>2</sub>	1.36
LOI	7.4

**Table 1: Soil Properties (Maskell et al., 2014)**

### 3.2 Primary Stabiliser

The potential for extruded earth bricks to be stabilised using cement and lime was investigated by Maskell et al. (2014) using extruded small scale bricks. CEM II 52.5N cement and hydrated lime was used in this investigation and will allow for a direct comparison to Maskell et al. (2014).

### 3.3 Metakaolin

The metakaolin used for this study was MetaStar® 501, manufactured by Imerys (2014), which is commercially advertised for concrete applications. The quoted typical values of the metakaolin used are shown in Table 2.

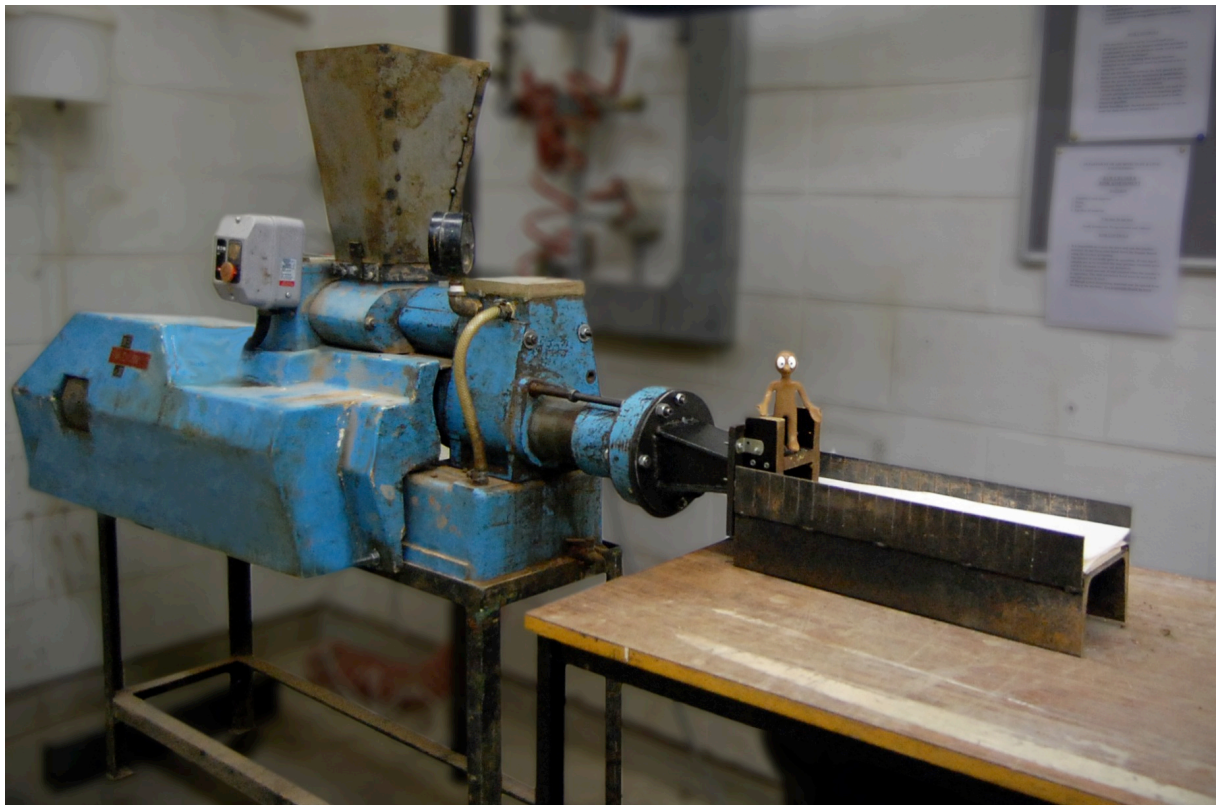


**Table 1: Metakaolin properties (Imerys, 2014)**

Properties	Values
Average Particle Size	1.2 $\mu$ m
Specific gravity	2.5
pH	2-6

### 3.4 Sample preparation and testing methods

The production of full size bricks using commercial methods of manufacturing was not feasible so a method of small-scale brick extrusion, as discussed by Maskell et al., (2012), was used. Small-scale bricks that measured nominally 72 mm by 34 mm by 22 mm thick (1/3 linear scale) were manufactured using a bench top vacuum extruder, as in Figure 1.



**Figure 1: Bench top vacuum extruder (Maskell et al., 2012)**

The mixture was prepared in a pan mixer by first dry mixing metakaolin with the soil and then adding 5% of the primary stabiliser by dry mass of the soil. Distilled water was then added into this dry mix and subsequently mixed for a further ten minutes. As the addition of cement or lime with metakaolin changes the plasticity properties, water was added to achieve the plastic flow required for extrusion of the material. The moisture content at which the bricks were extruded at, referred to as the Extrusion Moisture Content (EMC) (Maskell et al., 2014)

The physical and mechanical properties of bricks stabilised with cement and lime are a result of complex interactions between stabiliser type and the amount used. The ICT has also been shown to be key in the resulting properties, particularly with early age strength development (Maskell et al., 2014). Because of the influence of metakaolin on early age strength of Portland cement based concretes, the addition of varying amounts of metakaolin will potentially change these properties further (Sabir et al., 2001).

The effect of ICT was investigated by curing samples of bricks at 20°C, 60°C and 105°C. Following extrusion, all of the bricks were stored in a conditioning room (20 °C +/- 0.5 °C and 62.5% +/- 2.5% Relative Humidity) for two days. One sample of bricks was artificially dried in an oven at 60 °C with another sample dried at 105 °C, and another remained in the conditioning room. Following two days at these conditions all samples were then stored in the conditioning room until testing. Commercially fired bricks would typically following the two day drying at 60°C before being fired and therefore, the stabilised unfired bricks could be readily adopted into conventional practices. The other drying temperatures were used to investigate the ICT effect and are comparable to Maskell et al., (2014).

Compression testing of all the specimens was undertaken at 7, 14 and 28 days to investigate the development of strength. To assess the 'dry' and 'wet' performance of the bricks for each sample group, half were tested at ambient conditions and the other were fully immersed in distilled water for no less than 16 hours prior to testing. The specimens remained uncapped during compression testing, as Maskell et al., (2012) showed there was no requirement for capping for this type of

sample. Six samples of each group were tested allowing for analysis based on the averages and variance to be undertaken.

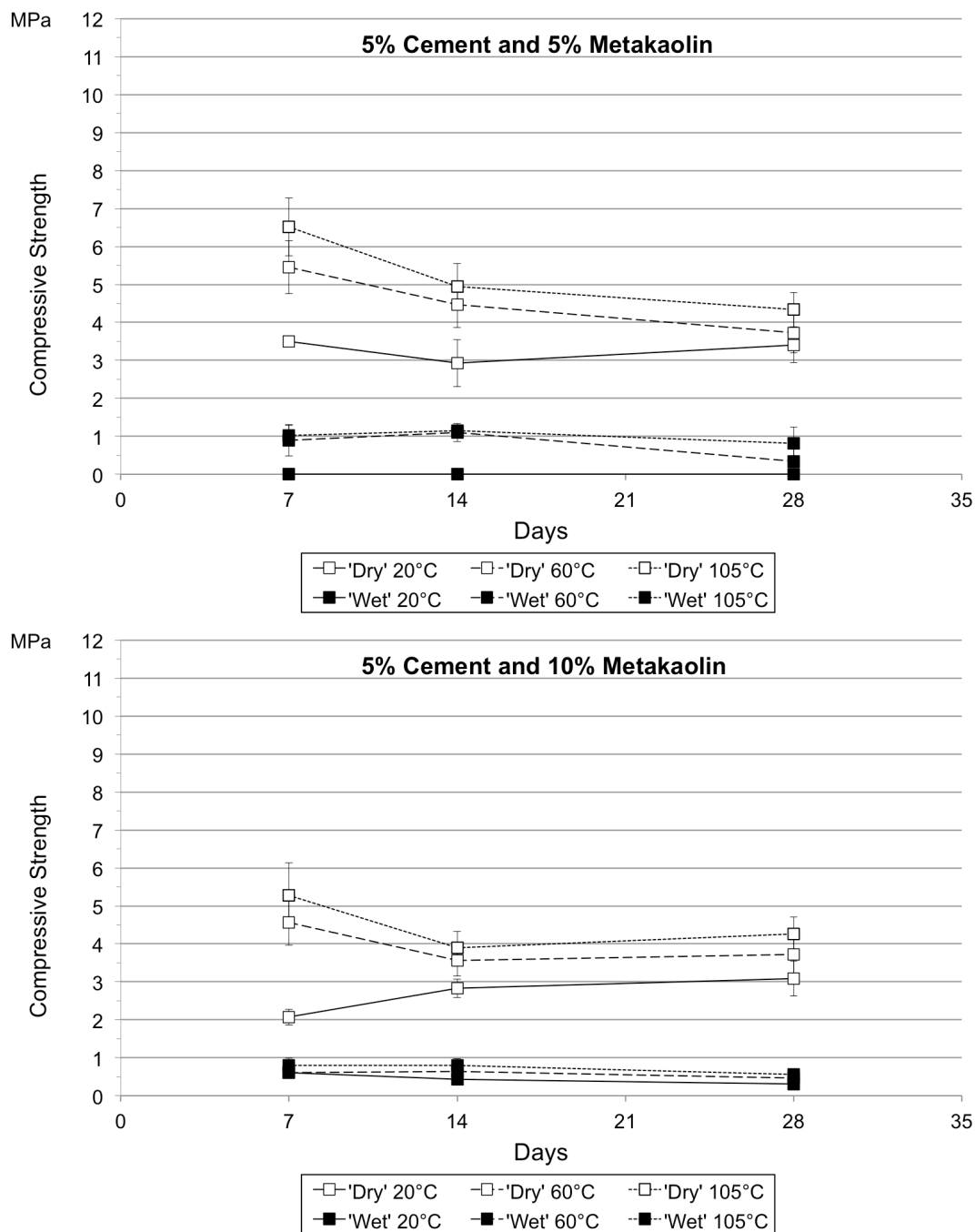
## **4 Results and discussion**

The following section discusses the individual results of the variation in primary stabiliser, metakaolin addition mass fraction and ICT.

The mass fractions of metakaolin added were either 5% or 10% of the dry soil only. The effect of metakaolin is compared to the equivalent stabilised sample groups presented by Maskell et al. (2014).

### **4.1 Cement**

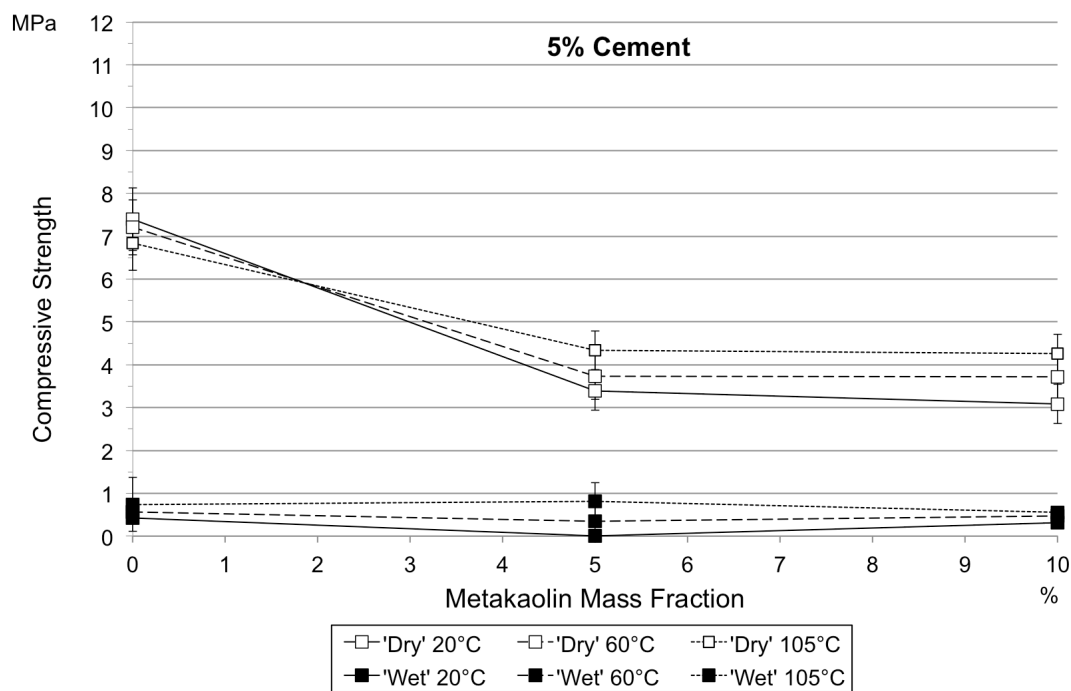
Only a 5% mass fraction of cement with the addition of 5% and 10% metakaolin were tested. The bricks were extruded at an average EMC of 17.6% and average dry density of  $1558\text{kg/m}^3$  with insignificant variation in density or moisture content with respect to the 5% and 10% mass fraction of metakaolin used. The results of the compression tests on the cement and metakaolin stabilised small scale brick specimens are presented in Figure 2, with the error bars indicating the 95% confidence interval.



**Figure 2: Compressive strength for 5% and 10% metakaolin addition to 5% cement**

The majority of the small scale bricks showed an improvement compared to an unstabilised sample compressive strength from Maskell et al., (2014) with only one exception. There was a reduction of strength with increasing age, especially between 7 and 14 days. This reduction in strength is attributed to the changing moisture content of the units in agreement with Heath et al., (2009). The moisture content of the bricks with 5% metakaolin initially cured at 20°C reduced by 3.3% between testing at 7 and 28 days whereas the moisture content of the equivalent bricks

initially cured at 105°C increased by 2.1% between testing at 7 and 28 days. Regardless of the initial curing conditions, at 28 days the samples had a similar moisture content. Figure 3 shows that the 28 day strengths were not improved by the addition of metakaolin to samples stabilised with 5% cement. This can be partially attributed to a 13% reduction in the density when metakaolin is added to the cement stabilised bricks.



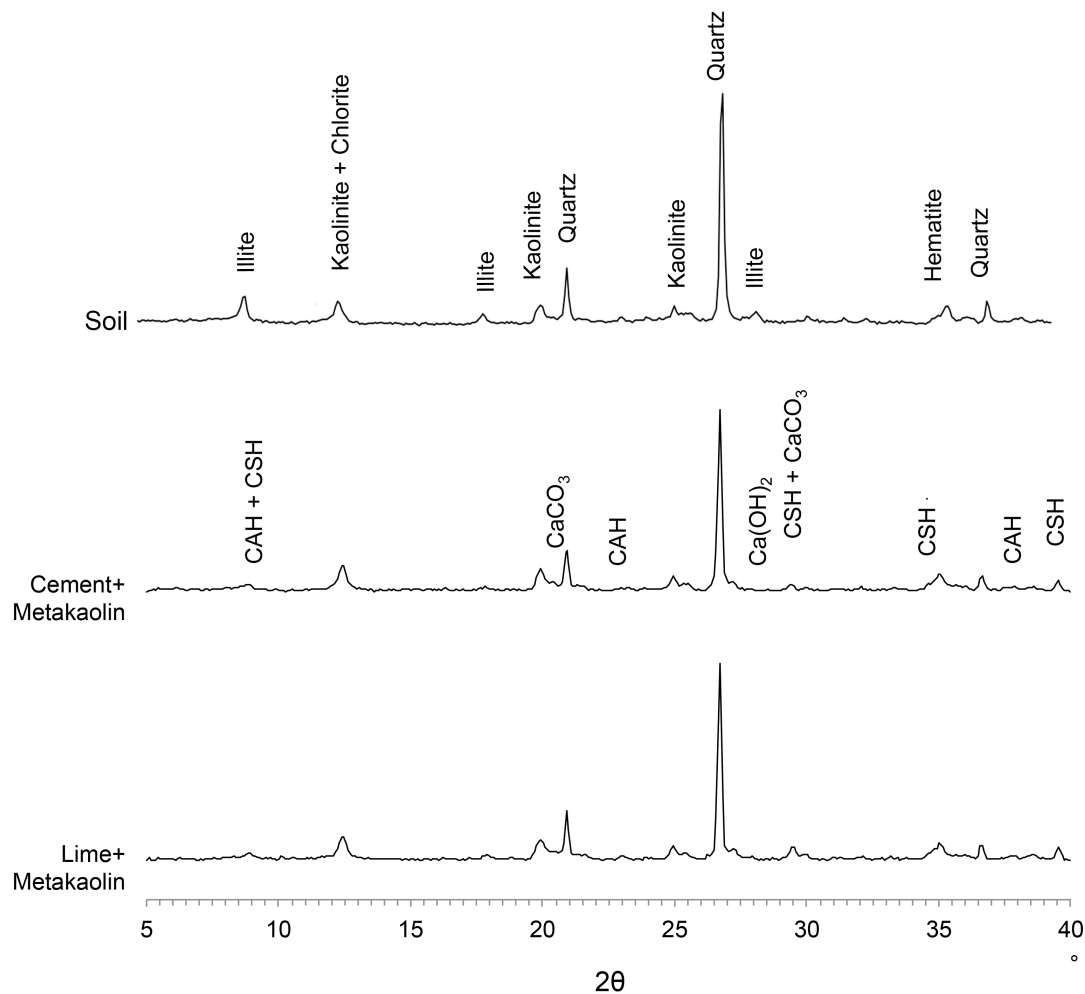
**Figure 3: 28 Day compressive strength 5% cement stabilised with varying metakaolin content**

All the small-scale bricks were able to be tested under 'wet' conditions achieving a compressive strength no greater than 0.80MPa.

The maximum 28 day 'dry' compressive strength with 5% cement was 4.33MPa and was achieved with 5% metakaolin addition and initially cured at 105°C. The addition of metakaolin decreased the 'dry' strength of the 5% cement stabilised bricks by an average of 53%. The 'wet' strength had no apparent trend with respect to the curing conditions or metakaolin content.

Following the 28 day testing, the specimens with the addition of 5% cement and 10% metakaolin were crushed and prepared for XRD analysis, as shown in Figure 4. The difference in the spectra in the range of 5–13° is attributed to the change in analysis technique, with the plain soil samples

analysed using small capillary collector compared to a flat plate collector for the stabilised samples. As identified in Figure 4, there are peaks present in the cement and metakaolin spectra that indicate the presence of CSH, CAH and Calcium Carbonate ( $\text{CaCO}_3$ ), showing that pozzolanic reactions had occurred. The spectra is still dominated by the minerals of the soil, and therefore the interaction between these phases and the soil particles is similar to those mechanisms discussed by Maskell et al., (2014).



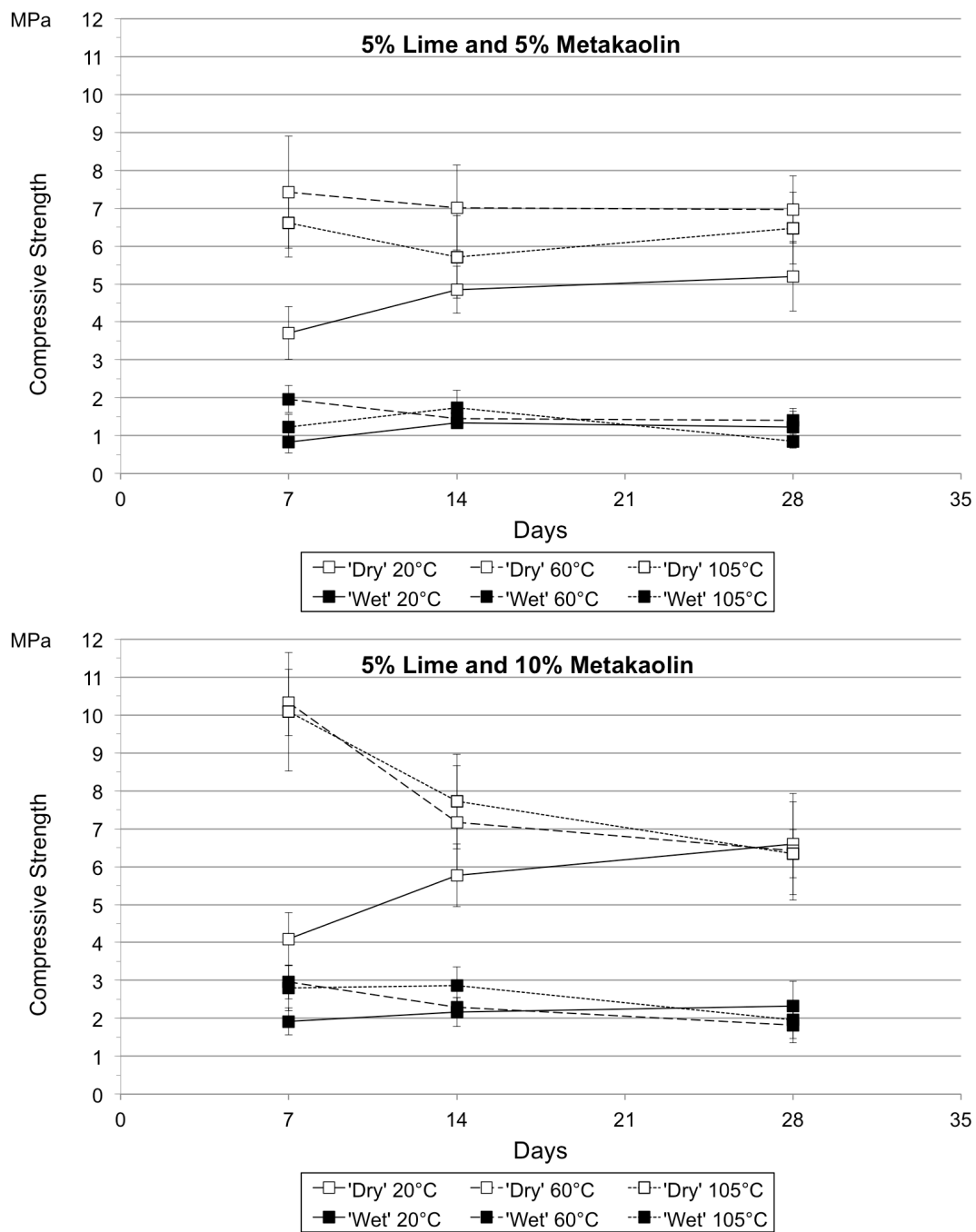
**Figure 4: XRD Spectra comparison of the metakaolin stabilised small scale brick specimens**

From the XRD spectra, it is noticeable that calcium hydroxide is not identified. While Portlandite would be an expected product from cement hydration, it was expected that it would react with the metakaolin to form further cementitious gel phases. While these phases were intended to increase the strength of the units, it has had the opposite effect. This is due to the complete

removal of calcium hydroxide that is unable to react with clay minerals present as suggested by Maskell et al., (2014). Wild et al., (1996) observed a similar decrease in strength of metakaolin based cement mortars due to the development of an inhibiting layer preventing reactions with calcium hydroxide with Wild and Khatib (1997) commenting that at infacial zones there is a low density of cement particles present. As a result there was no interstitial bonding between the clay minerals and the cementitious matrix. The matrix is not sufficient to completely encapsulate the mineral that ultimately leads to a decrease in strength.

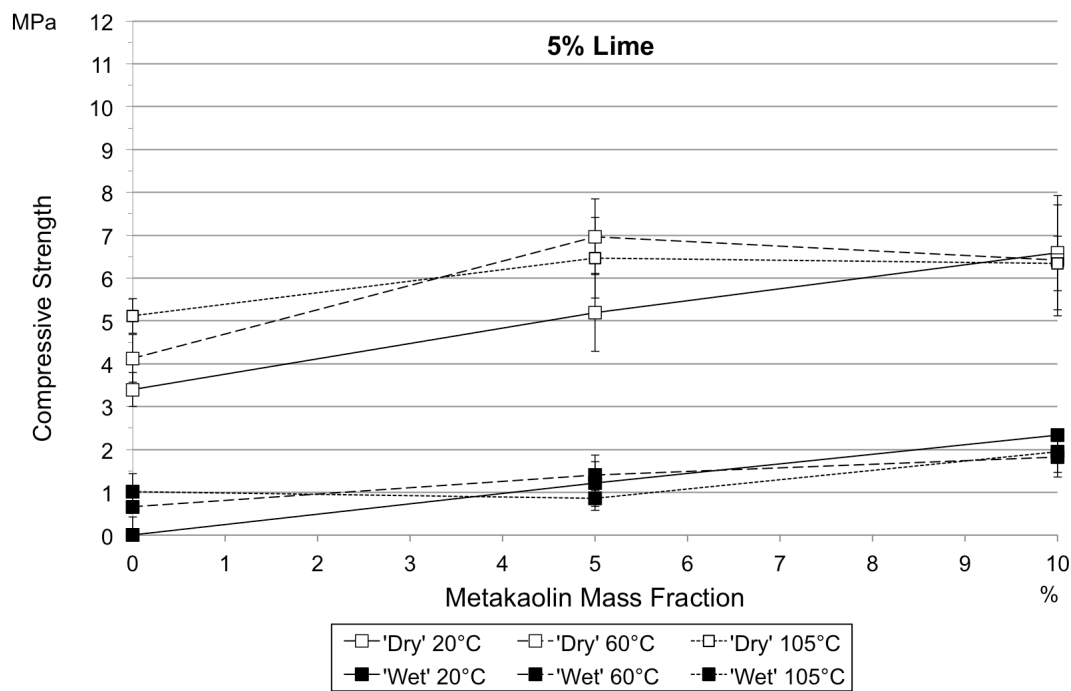
#### 4.2 Lime

The results of the compression tests on the small-scale brick specimens with lime and metakaolin stabilisation are presented in Figure 5, with the error bars indicating the 95% confidence interval. The average dry density of all the lime stabilised small scale bricks tested was  $1526 \text{ kg/m}^3$  with a Coefficient of Variation (CV) of 1.28%. The addition of metakaolin significantly increased the EMC and decreased the dry density compared to lime only stabilised specimens which had an average dry density of  $1764 \text{ kg/m}^3$  (Maskell et al., 2014).



**Figure 5: Compressive strength for 5% and 10% metakaolin addition to 5% lime**





**Figure 6: 28 Day compressive strength for 5% lime stabilised with varying metakaolin content**

There is a noticeable improvement of compressive strength with the addition of metakaolin for the brick stabilised with 5% lime, in spite of the decrease in density. There is no significant change in strength when the addition of metakaolin increased from 5 to 10% with the exception of the 5% lime specimen with the ICT of 20°C as can be seen in Figure 6.

As observed with cement as the primary stabiliser, there is a reduction of strength with increasing age of the specimens cured at a higher temperature. For the bricks with 10% metakaolin initially cured at 20°C, the moisture content reduced by 5.1% between testing at 7 and 28 days while the moisture content of the equivalent bricks initially cured at 105°C increased by 1.2% between testing at 7 and 28 days. Similar behaviour was measured with the specimens with 5% metakaolin addition, but to a lesser effect.

The 'wet' compressive strength showed greater dependency on increasing mass fractions of metakaolin. The addition of metakaolin increased the 28 day 'wet' compressive strength for all the lime stabilised samples, and the majority of the 7 and 14 day results.

Following the 28 day testing the specimens with 5% lime and 10% metakaolin were crushed and subjected to XRD analysis, as seen in Figure 4. It can be seen that the spectra of the lime is strongly correlated to the spectra of cement, indicating the pozzolanic reactions had occurred due to the presence of CSH, CAH and  $\text{CaCO}_3$  as with the cement. Although the intensity of peaks is not a simple indication of quantity, the area of each peak associated with the different pozzolanic phases are greater with lime than with cement, indicating a potentially greater reaction and hence higher compressive strength. The expected increased pozzolanic reactivity and the additional involvement of the soil particles (Reddy, 2013) within this pozzolanic reaction is most likely the cause of the improvement. Unlike the reaction mechanisms with cement where the calcium hydroxide predominantly reacted with the metakaolin, it is likely that a portion of the lime reacted with the metakaolin but also the clay mineralogy that strengthen the matrix formed, similar to the discussion presented by Wild and Khatib (1997). The strong correlation in the XRD analysis for cement and lime stabilisation but with a noticeable difference in compressive strength, indicates that the XRD analysis can identify strength giving phases but has limited use for quantification of strength development.

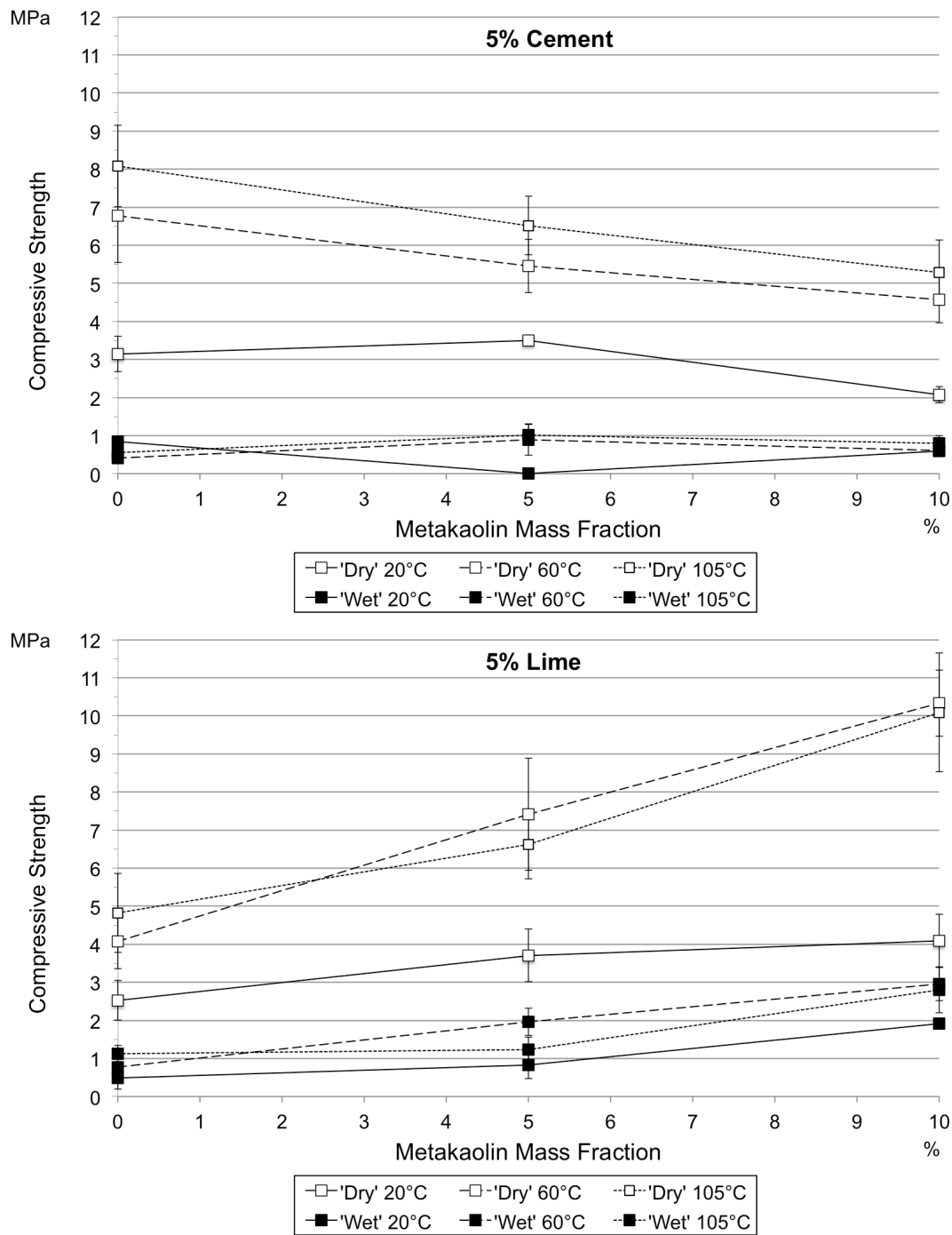
#### 4.3 Effect of Metakaolin

The effect of the addition of metakaolin to cement and lime is shown in Figure 3 and Figure 6 respectively. In addition to varying metakaolin content, the initial curing temperature was varied with bricks tested both 'dry' and 'wet' at 7, 14 and 28 days. With six replicates of each, this represents a total of 432 small-scale bricks tested.

For the equivalent ICT, only the addition of 10% metakaolin to 5% cement reduced the 'dry' strength to less than an unstabilised sample. However, the addition of metakaolin decreased the 28 day strength of all the cement stabilised bricks while increasing all of the lime stabilised bricks compared to the metakaolin free controls.

The strength development under both 'dry' and 'wet' conditions has been presented for the individual stabilisers, and can be seen in Figure 2 and Figure 5. It can be seen from Figure 7 that the development of strength by 7 days is similar to that of 28 days. The increasing addition of

metakaolin reduces the strength of the bricks stabilised with 5% cement with the exception of the addition of 5% metakaolin with an ICT of 20°C that had no significant effect. The addition of metakaolin to 5% lime stabilised bricks increased the 7 day strengths for all specimen groups. The greatest increase in 7 day 'dry' strength was achieved through increasing the ICT. The addition of 10% metakaolin with an ICT of 60°C resulted in an improvement of strength of 154% compared to the sample group without metakaolin. The early age development in wet strength shows similar relationship. As with the discussion regarding the 28 day strength of the addition of cement and lime stabilised bricks, there is not an apparent optimum in the range of mass fractions tested. This is not in accordance to previous work (Sabir et al., 2001) and indicates that there are fundamentally different mechanisms involved, as discussed above.

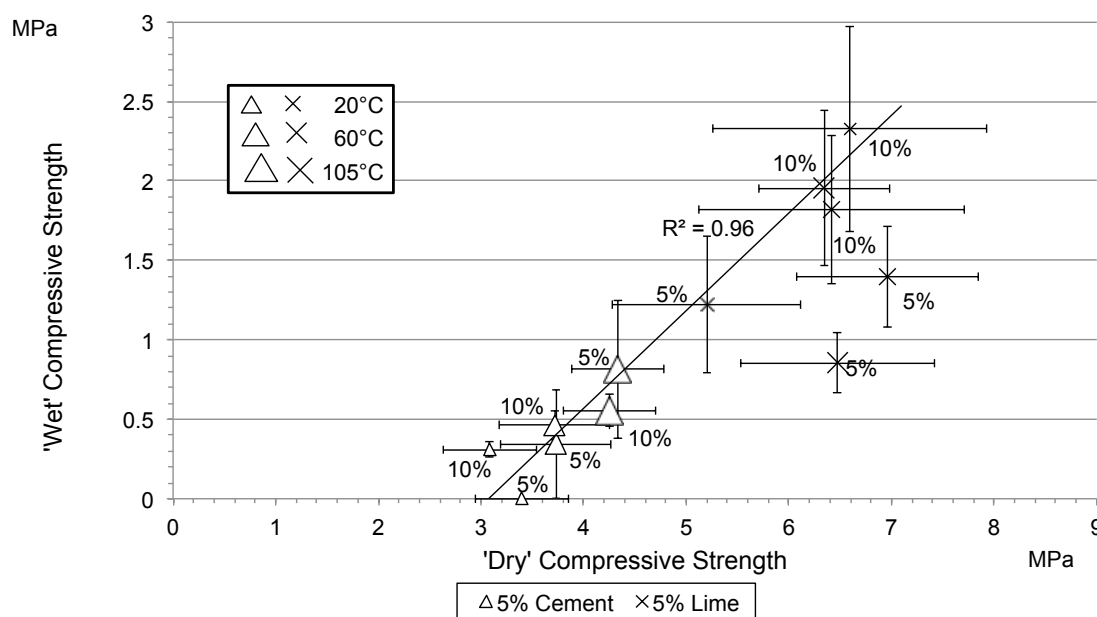


**Figure 7: 7 Day compressive strength for cement and lime stabilised samples with varying metakaolin content**

The primary intention of the metakaolin addition was to increase the 'wet' compressive strength. The greatest 'wet' strength achieved was 2.96 MPa and was achieved after 7 days with a 10% addition of metakaolin to 5% lime with an initial ICT of 60°C. At 28 days the maximum 'wet' compressive strength was 2.33 MPa which was achieved with a 10% addition of metakaolin to

5% lime with an initial ICT of 20°C. The equivalent sample without metakaolin completely disintegrated following immersion.

A relationship between the 'dry' and 'wet' compressive strength of the stabilised specimens was observed by Maskell et al. (2014) with the relationship differing according to the primary stabiliser used. The relationship for the specimens that included metakaolin can be seen in Figure 8. The specimens with the addition of 5% metakaolin and 5% lime with elevated curing conditions appear to be outliers and were not included in the best fit line in Figure 8. This indicates that the stabilisation mechanism has been changed by the addition of metakaolin. This is expected when metakaolin is used with cement and lime due to the enhancement of pozzolanic reactions. The 'dry' strength is therefore a reasonable indicator of 'wet' compressive strength regardless of primary additive used, when metakaolin is used.



**Figure 8: 28 Day relationship between 'dry' and 'wet' strength for various metakaolin contents**

## 5 Summary and conclusions

This paper has presented results from testing on lime and cement stabilised soil specimens with the addition of metakaolin. Small-scale brick samples were tested in compression for a measure

of the effectiveness of the stabilisation method. The results were compared against minimum strength criteria of 2.9 MPa under 'dry' conditions and 1.0MPa under 'wet' conditions.

Although there is literature concerning the reactions between metakaolin and the primary stabiliser, there is no available literature concerning how these binders interact with earth for any earthen construction method, and therefore no comparison to previous work can be made. While the soil is regarded as inert with respect to cement stabilisation, the inherent physiochemical structure of the soil can react with lime.

The effect of the addition of metakaolin on the 'dry' and 'wet' compressive strength was varied depending on the primary stabiliser used. Lime and metakaolin achieved the greatest compressive strength compared to cement and metakaolin. The greatest 28 day compressive strength achieved was 6.96 MPa, for the sample with 5% lime and 5% metakaolin initially cured at 60°C. While this addition of metakaolin increased the 'dry' compressive strength for all the samples with 5% lime, it decreased all the samples for 5% cement. This clearly shows that the addition of metakaolin is not universally suitable when requiring an increase in 'dry' compressive strength.

The addition of metakaolin did not significantly affect the 'wet' compressive strength of the cement stabilised bricks while it did improve the 'wet' strength of the lime stabilised units. All of the lime and metakaolin bricks achieved an average sample strength greater than 1.0MPa, with the exception of 5% metakaolin addition with an ICT of 105°C.

The only specimens that achieved and reliably exceeded the minimum 'wet' criterion were the specimens with 5% lime and 10% metakaolin regardless of ICT. The 'dry' and 'wet' compressive strength has been shown to be dependent on the mass fraction of the metakaolin and the ICT.

This research has shown that the pozzolanic stabilisation methods are fundamentally affected with the addition of the pozzolan metakaolin and that these mechanisms are different with clay minerals present. When metakaolin is added to lime significant compressive strengths can be achieved that meet minimum criteria for structural applications. Further research into the

embodied impact of the masonry units is required to verify the potential savings even when various stabilisers are required to ensure structural use.

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